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Temporal variation in a population biomass index for Cambridge Bay Arctic Char, *Salvelinus alpinus* (L.), in relation to large-scale climate variables

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Arctic Char, *Salvelinus alpinus* (L.), is an important target species for Commercial, Recreational and Aboriginal (CRA) fisheries around Cambridge Bay, Nunavut. Since 1972 a fishery-independent survey, involving experimental gillnet and weir enumeration, has been conducted in August and September at traditional fishing locations at the mouths of seven river systems. A population biomass index, weight-based catch per unit effort (CPUE), was generated using total numbers of individuals per census and length-weight relationships. Overall, a twelve year CPUE series was available. No significant differences in log-transformed CPUE were found between gear types (F=0.02, p=0.90) or months (F=2.96, p=0.08). August gillnet CPUE data were selected for standardization because it showed a stronger temporal variation in CPUE through the time series after CPUE data from the different gears were aggregated.

Three large-scale climate-related variables, the north Atlantic oscillation index (NAO), the Arctic oscillation index (AOI), and northern hemisphere sea surface temperature (NHSST), were included to estimate Arctic Char CPUE when enumeration information was not available. Significantly positive correlations between log-transformed CPUE and wintertime (March) NAO (r=0.76, p=0.01) and AOI (r=0.79, p<0.005), with a five-year lag, were found. No significant relationship was found between CPUE and NHSST (p>0.05). Using posterior parameters in a robust normal regression model, estimates of CPUE from wintertime AOI were generated with contingent agreement between observed and predicted values (χ^2=0.01, p>0.99). This approach is promising for further application of harvest statistics and the population biomass index to a population production model for Arctic Char integrating uncertainties from temporal variation in gear operations, stock status, and large-scale climate indices. Nevertheless, the potential associations between large-scale climate indices and local climate variability, and between climate variability and Arctic fish populations, remain to be demonstrated and established.

Variation temporelle dans un indice de biomasse de population pour l'omble chevalier, *Salvelinus alpinus* (L.), de Cambridge Bay, relativement à des changements climatiques à grande échelle

RÉSUMÉ

L'omble chevalier, *Salvelinus alpinus* (L.), est une espèce cible importante pour les pêches commerciales, récréatives et autochtones (ACR) autour de la Cambridge Bay, au Nunavut. Depuis 1972, un relevé indépendant de la pêche, qui comporte un filet maillant expérimental et l'énumération à un barrage, a été effectué en août et en septembre aux lieux de pêche traditionnels aux embouchures de sept systèmes fluviaux. Un indice de biomasse de la population, avec captures par unité d'effort (CPUE) basé sur le poids, a été généré à l'aide du nombre total d'individus par relevé et des relations longueur-poids. Au total, une série de CPUE de douze ans était disponible. Aucune différence significative n'a été relevée dans les CPUE ayant subi une transformation logarithmique entre les types d'engins (F=0,02, p=0,90) ou les mois (F=2,96, p=0,08). Les données sur les CPUE au filet maillant en août ont été choisies pour la normalisation puisqu'elles montraient une variation temporelle plus forte dans les CPUE tout au long de la série chronologique après l'agrégation des données sur les CPUE relatives à différents engins.

Trois variables à grande échelle liées au climat, l'indice d'oscillation nord-atlantique (NAO), l'indice d'oscillation arctique (AOI) et la température de la surface de la mer de l'hémisphère nord (NHSST), ont été incorporées aux estimations des CPUE pour l'omble chevalier lorsque l'information sur l'énumération n'était pas disponible. On a découvert des corrélations positives significatives entre les CPUE ayant subi une transformation logarithmique et le NAO hivernal (en mars) (r=0,76, p=0,01) et l'AOI (r=0,79, p<0,005), avec un décalage de cinq ans. Aucune relation significative n'a été établie entre les CPUE et la NHSST (p>0,05). En utilisant les paramètres postérieurs dans un modèle de régression normal robuste, on a généré des estimations des CPUE à partir de l'AOI hivernal avec un accord contingent entre les valeurs observées et les valeurs prédites (χ^2=0,01, p>0,99). Cette approche est prometteuse pour ce qui est des applications futures des statistiques de récolte et de l'index de biomasse de la population à un modèle de production pour la population d'ombles chevaliers intégrant les incertitudes des variations temporelles dans l'utilisation d'engins, l'état du stock et les indices climatiques à grande échelle. Néanmoins, les associations potentielles entre les indices climatiques à grande échelle et la variabilité du climat local, et celles entre la variabilité du climat et les populations de poissons dans l'Arctique, restent encore à démontrer et à établir.

INTRODUCTION

Arctic Char, *Salvelinus alpinus* (L.), is a circumpolar salmonid with an extensive distribution over coastal estuaries and freshwater habitats around the northern hemisphere (Scott and Crossman 1998). In eastern North America, its latitudinal range is dispersed from northern Ellesmere Island (c. 84°N) to New England (c. 43°N; Power et al. 2005). Throughout its use of diverse habitats, the species exhibits considerable phenotypic plasticity and adaptations to large-scale ecosystem changes. Consequently, a large number of characteristic hierarchies exist for the ecological speciation of Arctic Char, including life history types (e.g., anadromous or non-anadromous; Rikardsen et al. 2000, Power et al. 2005), ecotypes (e.g., pelagic or benthic forms; Adams et al. 1998), trophic types (e.g., planktivore or piscivore; Byström, 2006, Amundsen et al. 2010), evolutionary lineages (e.g., subspecies, biological stocks; Brunner et al. 2001), as well as variants within many of the above types (e.g., life history variability; Reist et al. 1995; Babaluk et al. 2007). Despite having similar age structures, significant divergences in length-at-age (Loewen et al. 2010), fecundity (Power et al. 2005), maximum size (Chavarie et al. 2010), and feeding habits have been found between anadromous and lake-resident (landlocked) morphometric components (Rikardsen et al. 2000). Because of its close trophic linkages and seasonal migrations between marine and freshwater habitats, Arctic Char is a cornerstone species, affecting the structure and function of the Arctic aquatic ecosystem.

In addition to its extraordinary importance to Arctic ecosystems, Arctic Char is highly sought by Inuit for commercial and subsistence uses. Through long-term fisheries development, Arctic Char populations have proven responsive when faced with increasing human demands for consumption, expanding exploration for gas, oil and mineral resources, and changes in environmental productivity. Combined with various vectors of anthropogenic activities, Arctic Char is somewhat vulnerable to the increasing impacts of global climate change on sub-Arctic and Arctic habitats (Reist et al. 2006). Despite increasing concerns regarding climate change impacts, especially for the adaptation and vulnerability of Arctic fisheries, there is still limited information available on the biological characteristics of Arctic Char, which impedes the creation of stock assessment and fisheries management frameworks. Such being the case, understanding variability in population production, measured by catch per unit effort (CPUE) and other related population attributes, is desirable for developing fisheries monitoring protocols in exploited systems (Hilborn and Walters 1992).

CPUE is a common index used to delineate time-varying trends in population size under multiple pressures, such as exploitation, local environmental degradation, habitat fragmentation, and large-scale climate changes (Maunder and Punt 2004). CPUE information should be used cautiously as an index of abundance. Improper use of it may account for the demise of a fishery when the underlying assumptions are not adequately met (Rose and Kulka 1999). For example, in some cases the assumption of a linear relationship is violated, when high CPUE is maintained in spite of declines in abundance, which is termed hyperstability (Harley et al. 2001). Ignoring the hyperstability is believed to result in the overestimation of relative abundance and an underestimation of fishing mortality (Crecco and Overholtz 1990). In particular, when targeted fish populations are exploited by multiple gears or when changes in gear type or configuration occur, the resulting CPUE is greatly subject to the gear changes as well as targeting practices from single species to multi-species bycatch pursuits (Hilborn and Walters 1992). In addition to fishing power, environmental variables also have large, indirect influences on catchability. Examples of this include a reduction in catchability of Yellow Tuna (*Thunnus albacares*) by the 1981-1983 El Niño (Maunder et al. 2006).

It is critical that a CPUE series is standardized to eliminate inherent noise from differences in the types of sampling gears, capture efficiencies, survey vessels, seasons, as well as quantity and quality of habitats sampled (Hilborn and Walters 1992, Quinn and Deriso 1999, Hubert and

Fabrizio 2007). Among recent developments on the standardization of CPUE, a number of analytical models have been created. Battaile and Quinn (2004), for example, employed a general linear model to standardize the CPUE of Alaska walleye pollock (*Theragra chalcogramma*). Bishop et al. (2004) applied classical generalized linear regression (GLM), generalized mixed models (GMM), generalized estimation equations (GEE), and generalized linear mixed models (GLMM) to the standardization of catch and effort data of Australian northern prawn *(Penaeus semisulcatus, P. esculentus,* and *Metapenaeus endeavouri)* fisheries.

Arctic Char is an important species for commercial and subsistence fisheries near the community of Cambridge Bay, Nunavut. A series of fish plant sampling and field experiments have been carried out by many researchers from Fisheries and Oceans Canada (DFO) since 1972. Among these, CPUE was accumulated sporadically by using gillnet or weir in August and September, expressed as an index of abundance but never standardized. A standardized CPUE series was needed to monitor the population dynamics of Arctic Char around Cambridge Bay and to determine the management targets associated with changing fishing strategies and ecological environment. To that end, this study was undertaken to address the following objectives to:

- summarize fishery development, including commercial and subsistence components;
- establish individual- and weight-based CPUE series from DFO-designed experimental sampling programs;
- standardize the CPUE in combination with month, year, gear and environmental effects; and
- correlate large-scale climate covariates with CPUE to account for biological production variations under altering climate scenarios.

MATERIALS AND METHODS

STUDY AREA

Situated on the southeast coast of Victoria Island (*Kitlineq*) in the Canadian Arctic Archipelago, between Dease Strait and Queen Maud Gulf, Cambridge Bay (69°6'N, 105°8'W) is a transportation and administrative center for the Kitikmeot Region (Figure 1). The traditional Inuinnaqtun name for the area is *Ikaluktuutiak* (old orthography) or *Iqaluktuttiaq* (new orthography), meaning "good fishing place". Historically, all river systems in the area were likely fished for subsistence uses (DFO 2004).

The weather conditions in Cambridge Bay are largely influenced by the geographic position of Victoria Island and the hydroclimate patterns of the Arctic Ocean. Monthly average temperatures above 0°C occur in June through August, when rainfall is the highest, peaking at more than 30 mm on a daily basis. Between 1950 and 2010, the monthly temperature varied between -33.50 ± 0.40°C in February and 8.35 ± 0.20°C in July, with an annual average of -14.58 ± 0.17°C (Figure 2). During the winter (December to March), the air temperature was below -30°C and average daily snowfall depth was >5 cm. The overall amount of combined precipitation, with rainfall and snow together, showed a single period of seasonal variation that was positively related to air temperature (r=0.5568, p<0.0001, Climate Weather Office). Monthly average precipitation was more than 10 mm between June and October. The general climate pattern was for wetter and warmer weather in summer and early fall, while drier and colder conditions prevailed during the winter.

FISHERIES

Beginning as early as 1960, fishing for Arctic Char usually occurs in mid-July, with fishers seeking sea-run migrants at the mouths of the Lauchlan, Halovik and Paliryuak rivers and in the northern waters of Wellington Bay. Sea-return migrants are targeted in mid-August and early September in several river mouths around Cambridge Bay (Yaremchuk et al. 1989, Day and de March 2004). Initially, gillnets with various mesh sizes were used. Later, a minimum mesh size of 140 mm was established in 1962. Prior to 1994, gillnets were used exclusively to harvest Arctic Char in the Halovik and Jayco rivers. From 1994 to the present, these two fisheries have been conducted with weirs, except at Halovik in 1995 and 2001, and at Jayco in 1995 when gillnets were used (Day and Harris 2013). Arctic Char have also been harvested in HTA Lake with weirs since this fishery began in 1988. From the onset of the commercial fishery to today, harvesting in the Ellice, Paliryuak, Lauchlan and Ekalluk rivers has been conducted exclusively with gillnets, except in 1994 and 1995 when weirs constructed of netting material were used at the Ekalluk River. All other Cambridge Bay weir fisheries used conduit weirs, which were described by Kristofferson et al. (1986).

DATA SOURCES

Catch per unit effort (CPUE)

Along with the development of Arctic Char fisheries, a DFO-designed fishery-independent survey, involving enumeration by experimental gillnets and weirs, has been conducted since 1972. Experimental gillnets (140 mm stretched mesh, 45.72 m (50 yards) long, and 2.13 m (7 feet) deep and weirs were used for data collection on occasions when plant sampling data were not available because the fishery did not always occur at each location monitored. Through collaborations among DFO scientists and the Nunavut Wildlife Management Board (NWMB), the fishing gears are set at river mouths to entrap sea-return migrants in August and September. Soak duration, the period during which the gear remains in the water, was kept to one day (24 hours). The measurement of CPUE was defined as the total number of individuals of the species caught by a standard gear in one day. The CPUE series available is limited to weir or gillnet enumeration in a number of years. In each of 1972, 1975, 1978, 1980, 1988, 1991, 1992, 2005, and 2006, a single enumeration was made using experimental gillnets in one of the following rivers: Ekalluk, Halovik, Paliryuak, or Jayco. In each of 1975, 1979-1981, and 1983, an experimental weir was deployed to enumerate anadromous migrants in a single fishing location in one of the following rivers: Ekalluk, Halovik, Jayco, and Launchlan. In addition to numeration of char harvested, a definite quantity of biological observations were conducted including sex and maturity on a yearly basis, whilst most fish were dressed (viscera and gills removed) prior to shipment to the fish plant. Sex and maturity stage were assigned via visual examination of the gonads with reference to a numerical grading system (Day and de March 2004). In terms of length and weight measurements, the abundance index was converted into a biomass-based index to support subsequent population dynamics model analysis.

Impacting covariates

Only 12 years of effort data were collected during 1972-2006, mixed with effects from two sampling gears, gillnet and weir, months of August and September, and years. As an alternative, we turned to monthly anomalies in macro-scale climate-related covariates to generate CPUE information for the time series when there were no experimental CPUE observations. These climate-related covariates included the north Atlantic oscillation index (NAO), the Arctic oscillation index (AOI) and northern hemisphere sea surface temperatures (NHSST). These statistical indicators have been extensively used to depict the effects of climate change on the earth ecosystems, especially the most serious environmental issues threatening the Arctic world (Arctic Climate Impact Assessment 2004).

STATISTICAL ANALYSES

Usually, CPUE data for exploited fish are critical information used to monitoring the exploited fish stocks and fishery management. It is expressed as a linear proportion to population abundance,

$$C/f = q \cdot N \tag{1}$$

Here, *C* and *f* are the quantities of catch and fishing effort invested, respectively. Parameter *N* is the number of individuals of the species caught under a unit effort and *q* is a measure of the catchability coefficient, the probability of being caught during one unit of fishing effort (Hubert and Fabrizio 2007).

Individual-based CPUE can be converted into a weight-based index, in combination with the relationship between total length (*L*: mm) and round weight (*W*: g) of Arctic Char, which is usually expressed by a power function,

$$W = a \cdot L^b \tag{2}$$

Here, *a* and *b* are regression coefficients.

The standardization of CPUE in this study was conducted using two statistical strategies: analysis of variance (ANOVA) and a robust normal regress model (RNRM). ANOVA was first employed to examine significant differences in CPUE under the interacting effects of month and gear type. A RNRM was then used to investigate the influences of time and large-scale climate parameters on the biomass index of Arctic Char. The RNRM belongs to a link function in an exponential family. A continuous distribution may be more appropriate if the catch is in a weight account (Maunder and Punt 2004). A skewness and kurtosis test for CPUE normality was explored by using Stata. As usual, the response variable (weight-based CPUE) was assumed to follow a normal probability distribution with mean μ and variance σ^2. Explanatory variables included year, AOI, NAO, and NHSST,

$$Y \mid X_1, \dots, X_p \sim N(\mu(\beta, X_1, \dots, X_p), \sigma^2)$$

$$\mu(\beta, X_1, \dots, X_p) = \beta_0 + \beta_1 X_1 + \dots + \beta_p X_p \tag{3}$$

$$= \beta_0 + \sum_{j=1}^{p} \beta_j X_j$$

where σ^2 and $\beta=(\beta_0,\beta_1,\dots,\beta_p)^T$ is the set of regression parameters under estimation. Generally, the alternative representation of the regression model is adopted by,

$$\ln(CPUE_i) = \beta_0 + \beta_1\, year_i + \beta_2\, AOI_i + \beta_3\, NAO_i + \beta_4\, NHSST_i + \varepsilon_i \tag{4}$$

where *year* denotes the observed time term, and items AOI, NAO, and NHSST are referred to the selected macro-scale climate-related variables. The uses of the representative month and years of time-lag of the variables were determined by a pair-wise correlation analysis at a critical level α=0.05. An error term ε is assumed to have a conjugate normal distribution with mean of 0 and standard deviation of σ^2. Deviance information criterion (DIC) was used for model selection and was implemented in the platform OpenBUGS v3.11 (Lunn et al. 2009), picking the best model with the smallest DIC (Carlin and Louis 2009). We ran two Gibber chains of Markov chain Monte Carlo (MCMC) samples of 3,000,000 iterations each, following a 500,000 burn-in period with a thin of 250 to generate a sequence of 10,000 samples for analysis.

RESULTS AND DISCUSSION

FISHERIES DEVELOPMENT

Two types of fisheries are responsible for the exploitation of Arctic Char around Cambridge Bay: commercial and subsistence harvests. During 1960-2010, the total commercial harvest ranged from 5.77 tonnes in 1962 to 67.94 tonnes in 1978, with an overall average of 41.17 ± 2.20 tonnes for seven fishing locations (Table 1). Among those major fishing locations, harvests from the Ekalluk and Jayco rivers jointly contributed more than 50% of the total harvest, with the remaining 47% coming from the Halovik, Lauchlan, Paliryuak, and Ellice rivers (Figure 3). The Perry River fishery accounted for less than 2% of the total harvest. In addition, variation in these fisheries primarily resulted from successive harvesting from the same stock (or sub-stocks; Kristofferson et al. 1984).

To prevent the over-exploitation of a single stock, the management of Arctic Char fisheries has been based on quotas and fishing license controls. In 1960, an entire watershed-based quota system was initially established. As fishing activities developed, especially a transition from a primarily gillnet fishery to the alternative use of gillnets and weirs, harvest varied with location. It became necessary to implement a river-specific quota system (Day and de March 2004). Since 1962, the quota system has been renewed in a timely manner to correspond to changes in commercial harvests and stock status (Table 2), but a minimum mesh size of 140 mm has remained fixed. The highest quota was 74 tonnes in 1979 and 1980, but has been maintained at 68 tonnes since 2004.

Historically, Arctic Char was an important food source for both humans and animals, but complete records of the human subsistence harvest do not exist. A recent Nunavut wildlife harvest study (Priest and Usher 2004) showed that the numbers of subsistence harvesters for Arctic Char in the Cambridge Bay area increased gradually from 23 in June 1996 – May 1997, to 55 in June 2000 – May 2001. Subsistence harvest of Arctic Char varied from 1,437 fish in 1997-1998 to 12,435 fish in 2000-2010, with an average of 6,461 ± 2,175 fish (Table 3). Within a year, the largest harvest (70%) occurred in July and August, while only 20% of the total harvest was taken in June and September. Assuming that the average size of a char from the subsistence harvest is similar to the average commercially harvested fish (3.5 kilograms), the annual subsistence harvest of Arctic Char is approximately 22,600 kilograms or about 50% of the annual commercial harvest. This rough estimate assumes that the mesh sizes used by subsistence harvesters were exactly the same as the nets used in the commercial fishery (Day and de March 2004). It should be noted that subsistence harvest figures from the Nunavut Wildlife Harvest Study are generally disputed by most Nunavut communities, and should therefore be treated with caution.

SELECTION OF STANDARD GEAR AND SAMPLING SEASON

According to the documentation for the DFO-designed survey, total individuals per census was initially enumerated and represented as the number-based CPUE. Using measurements from a sub-sample of these fish, the relationship between total length and round weight was described by a power function (Figure 4). Most biological samples (>95%) were from the Lauchlan, Halovik, Ekalluk and Jayco rivers. Among the regression relationships, the highest and lowest power coefficients were found in the Halovik and Ellice rivers, respectively.

In terms of the length-weight relationship, the arithmetic and geometric means of the biomass index (hereafter called CPUE) from experimental gillnets and weirs are summarized in Table 4. ANOVA found no significant effect of month (August vs September) or gear type (gillnet vs weir) on the pooled log-transformed CPUE (Table 5). Marginal differences were derived from month effects (F=2.96, p=0.08) but there was no effect of gear type (F=0.02, p>0.90) and there was no

significant interaction between month and gear type (*F*=1.80, *p*>0.20). It is reasonable to ignore month effects on CPUE because the DFO-designed experimental sampling normally occurred between August 10 and September 15. Compared with two sampling gears, two sets of the log-transformed CPUEs seemed to be much closer in August (*F*=0.65, *p*=0.44) than in September (*F*=1.50, *p*=0.26). Despite the consistent sample size, this is indicative of greater temporal variation in gillnet CPUE (median=0.1032, SE=0.0512) than weir CPUE (median=0.1287, SE=0.0423), which results in noticeable variability in the Arctic Char biomass index through the time series. Therefore, August gillnet samples were chosen to standardize the relative biomass index throughout the sampling series.

CLIMATE-RELATED COVARIATES TO ARCTIC CHAR PRODUCTION

During the winter season (represented by March), all three climate-related indices exhibited distinct temporal tendencies in the mid-1970s: evident positive anomalies in NAO and AOI versus remarkable negative anomaly in NHSST (Figure 5). In fact, there was a closely positive correlation between NAO and AOI (*r*=0.60, *p*<0.001). The cumulative sum of the control chart (CuSum) of the anomalies proved better for visualizing simple shifts in the trends of all of the climate indices. Years in which the value of CuSum changes are years when a regime shift occurs (Beamish *et al.* 1999). Positive values indicate above-average values of the accounting index and negative ones represent below-average or decreasing trends. Increases in regime shift indicators seem to occur eight years earlier in NAO than in AOI and NHSST.

As a result of the absence of a complete time series of weight-based CPUE, a pair-wise correlation was used to establish an empirical relationship between log-transformed CPUE and observed climate indices, such as NAO, AOI, and NHSST (Tables 6, 7, 8). The results showed that there were no significant correlations between log-transformed CPUE and NAO except for five-year and seven-year lags (Table 6). Positive correlations were found in January and March with a five-year lag, and in February and April with a seven-year lag. The most significant positive correlations were found between CPUE and March NAO (*r*=0.7551, *p*=0.0072) or AOI (*r*=0.7858, *p*=0.0041) with a 5-year lag. There was no correlation between log-transformed CPUE and NHSST. These results suggest that variability in Arctic Char population production may be influenced by changes in hemispheric and synoptic scale atmospheric circulation.

Combined with ANOVA and correlation analyses, the effects of month, year, and wintertime AOI on log-transformed CPUE were structured by a robust normal regression model (Table 9). The best model was found with respect to the combination of ln(CPUE) and AOI that produced the lowest DIC and standard deviation as well as the highest posterior mean precision (R^2_B). The models that included either a year-effect or a constant term generated the worst results.

Posterior values of model parameters and estimated CPUE are summarized in Table 10; these indicate similar outputs based on inputs of CPUEs in August and September. This means the result is insensitive to the month of sampling, which firmly supports the ANOVA results presented in an earlier section of this report. All Monte Carlo error values were <4%, which ascertained the effectiveness of the model estimates (Carlin and Louis 2009). The robust positive correlation between ln(CPUE) and AOI is shown in Figure 6; 72% of the observations (8 of 11 points) fell within the 95% confidence intervals. Overall, the first two observed values were evident outliers from the predicted trend due to observation errors (Figure 7). Furthermore, a Chi-square test showed contingent agreement between observed and predicted CPUEs (χ^2=0.0312, *p*>0.99).

INTERACTIONS BETWEEN LARGE-SCALE CLIMATE INDICES AND LOCAL CLIMATE

It is a well-known climate variable that is associated with high temperature and low pressure at a number of weather field centers. Research documented that strong positive anomalies occurred in the northwestern Atlantic Ocean when the Icelandic low was intense as a result of strong westerly winds flowing from the north over western Greenland (Barnston and Livezey 1987). The oscillation of the dominant wind patterns thus remarkably affected precipitation and temperature patterns (Hurrell 1995), as well as bottom temperature and circulation patterns in the north Atlantic (Barnston and Livezey 1987, Deser et al. 2010).

The atmospheric circulation and teleconnection patterns expressed by NAO, AOI, and NHSST are important controllers of various climatic events over various temporal (short or long-term) and spatial (local, regional, and global) scales in the northern hemisphere (Hurrell 1995, Beamish et al. 1999, Stige et al. 2006, Türkes and Erlat 2008, Hurrell and Deser 2010). These indices of large-scale climate modes provide an integrated measure of weather, and therefore can be linked more to the overall physical variability of the system than to any individual, local variable. The NAO index, for example, is associated with alternating high winter temperatures and low pressures between a number of centers, as well as having a possible connection with recruitment of North Atlantic cod (Stige et al. 2006) and the large fluctuation of Pacific Salmon (Beamish et al. 1999). Relationships between wintertime AOI anomalies and local climate variables for Cambridge Bay were explored, but no significant trends were detected. Over the time series of 1950-2009, Cambridge Bay air temperature from March to December, except April, appeared to be negatively related to wintertime AOI anomalies. After being normalized, the covariates displayed weakly negative trends in winter (March) and spring (May) (Figure 8), corresponding to increasing local air temperature while reducing winter AOI. Also, the precipitation-AOI interplay was negative in March and positive in May. This means that lower AOI values may lead to much heavier snowfall and colder temperatures in winter. While higher winter AOI values, it may trigger less snowfall as temperatures are low (ACIA 2004). Overall, the squared correlation coefficients varied from 5×10^{-5}~0.0248 and 7×10^{-5}~0.0607 for pairings between local temperature and AOI, and precipitation and AOI, respectively. These values, along with the lack of statistical significance, are insufficient to support the existence of cause-effect relationships. Further work is thus required in order to identify and establish the potential link(s) between AOI and local climate variability in the Cambridge Bay Area. This could involve integrating information on winter temperatures and precipitations with the timing of annual river-ice break-ups, as this will determine movements of Arctic Char into summer feeding areas.

IMPLICATIONS OF CLIMATE CHANGES ON ARCTIC FISHERIES

Profound changes in climate are believed to exert evident impacts on local environments and fisheries production. The mechanism of the asynchrony between climate and fisheries has proven difficult to establish empirically; demographic changes in fish recruitment and production are a promising linkage for nonlinear and non-stationary regime changes (Beamish et al. 1999, Greene et al. 2008). The Arctic is on the frontier of impact centers as a result of climate warming (Greene et al. 2008). Consequently, the influence of global climate change will result in increased precipitation, river discharge, and glacial as well as sea-ice melting. As freshwater escapes from the Arctic, it modifies vertical salinity-temperature stratification and horizontal circulation, as well as biogeographic range expansions (Hurrell 1995, Deser et al. 2010). Through a series of biological production processes and interactions with abiotic and biotic components, the resulting ecological response can be delineated as dramatic regime shifts in freshwater and marine ecosystems (Beamish et al. 1999, Greene et al. 2008). Therefore, changing weather conditions in the Arctic will not only alter atmosphere, ocean, and cryosphere interactions, but regulate fisheries populations through life-history changes, spawner-

recruitment relationships, and food-web dynamics, especially for highly migratory species such as salmonids (Beamish et al. 1999, Reist et al. 2006, Greene et al. 2008).

Under changing environmental scenarios, increasing evidence shows that variations in exploited populations and fisheries will result from a series of complex interactions among the natural evolution of population dynamics, multiple exploitation-related pressures and environmental forcing (Hilborn and Walters 1992, Lehodey et al. 2006). Temporal variation in fishery abundance is synchronized with climate changes over interseasonal, interannual, and decadal scales, as is exemplified by Northern Shrimp, *Pandalus borealis* (Greene et al. 2008), American Lobster, *Homarus americanus*, (Fogarty and Gendron 2004), salmons (Beamish et al. 1999), Atlantic Cod, *Gadus morhua* (Stige et al. 2006), and tuna and billfish, such as Albacore Tuna, *Thunnus alalunga*, and Bigeye Tuna, *T. obesus* (Rouyer et al. 2008). As a result of negative NAO conditions, which were predominant during the 1960s, Northern Shrimp thrived in colder bottom temperatures; they subsequently collapsed during a predominantly positive phase in the 1970s in the Gulf of Maine (Koeller et al., 2009). The collapse of the Newfoundland cod provided evidence that noticeable positive NAO values likely led to a failure in cod recruitment by modifying local environmental variables such as sea temperature, salinity, oxygen, turbulence, and advection (Stige et al. 2006). In contrast, significant increases in commercial landings of American Lobster were synchronized with noticeably positive NAO anomalies (Fogarty and Gendron 2004).

In this study, we found a significant correlation between Arctic Char CPUE (index of relative abundance) and wintertime AOI, suggesting a possible linkage between large-scale climate variability and fish population dynamics in the Canadian Arctic. Similarly, spatially structured covariates between NAO and CPUE have been documented for 169 tuna and billfish stocks throughout the Atlantic, for which CPUE fluctuations were not directly attributable to variation in fish abundance (Rouyer et al. 2008). Herein, a five-year lag effect between Arctic Char CPUE and winter AOI could suggest that large-scale climatic indicators affect char populations through the regulation of life-history traits. Referring to studies of Arctic Char biology, the age composition from commercial samples ranged from 3-22 years in Cambridge Bay during 1971-2009 (Day and Harris 2013). Related studies from lake systems in southern Baffin Island, Nunavut, documented age ranges of 3-17 years, with mean ages of 10-13 years and 8-9 years for anadromous and lake-resident mature fish, respectively (Loewen et al. 2010). Babaluk et al. (2007) reported an age range of 6-26 years for mature Arctic Char in lakes in Quttinirpaaq National Park, Nunavut, during 1990-2002. Therefore, it is reasonable to suggest that successful Arctic Char recruitment should synchronize with remarkable positive AOI events during colder, dryer winters (Figure 8), favoring over-wintering by Arctic Char (Read 2003). As a result of the accumulative effects of winter AOI, the recruitment of Arctic Char may benefit from cooler and wetter springs. The general patterns of density-dependent recruitment and the interactions between fishing-induced demographic changes and variations in biotic or abiotic carrying capacity undoubtedly need to take those factors into account in the future.

CONCLUSIONS

Abundance rates or relative abundance are usually measured for individuals of a studied population using a standard unit of effort. When describing biomass dynamics, scientists also use weight-based measures that are commensurate with quantitative length-weight ratios. When using CPUE information for stock assessments, a number of underlying assumptions have been proposed to ensure the applicability of data for fisheries assessment. The underlying assumption of using CPUE as an index of abundance or biomass is that the number or weight of fishes captured is proportional to the amount of effort expended. Time series of CPUE data are used to assess the efficacy of fisheries management actions through regulating the investment of fishing effort to monitor the declines or increases in abundance or biomass of the

exploited fish populations. In the case of Arctic Char inhabiting rivers and lakes around Cambridge Bay, harvest for commercial uses started in 1960 and the first field observations of catch rates occurred in August and September 1972 during a DFO-designed experimental gillnet and weir program. ANOVA found no significant differences in weight-based CPUE between the two gears. Despite the lack of significant differences in catch rates between sampling months, the CPUE series was standardized using gillnet data from August because it showed a stronger temporal variation in CPUE through the time series after CPUE data from the different gears were aggregated. Robust positive correlation, facilitated by Bayesian normal regression between the Arctic oscillation index (AOI) and CPUE, provided an alternative procedure for predicting the CPUE series when observations were not available. This approach is promising for further application of harvest statistics and the population biomass index to a population production model for Arctic Char integrating uncertainties from temporal variation in gear operations, stock status, and large-scale climate indices.

Such an over-simplified covariate rationale should be used cautiously because variations in fish populations and fisheries in the time series are the result of several embedded processes that occur at different spatial and temporal scales. The biological consequences of regime changes vary with the underlying attributes of the organism, niche availability and physical and biological system dynamics. Overall, the potential associations between large-scale climate indices and local climate variability, and between climate variability and Arctic fish populations, remain to be demonstrated and established.

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TABLES AND FIGURES

Table 1. Commercial harvest (tonnes) of Arctic Char from the estuaries of rivers around Cambridge Bay, Nunavut during 1960-2010.

Year	Lauchlan	Halovik	Paliryuak	Ekalluk	Jayco	Ellice	Perry	Sum
1960	0.00	0.00	0.00	15.88	0.00	0.00	0.00	15.88
1961				10.82				10.82
1962	0.00	0.00	0.00	5.77	0.00	0.00	0.00	5.77
1963	2.27	0.00	0.00	13.88	0.00	0.00	0.00	16.15
1964	0.00	0.00	0.00	15.50	0.00	0.00	0.00	15.50
1965	0.00	0.00	0.00	20.87	0.00	0.00	0.00	20.87
1966	0.00	0.00	0.00	16.78	0.00	0.00	0.00	16.78
1967	0.00	0.00	0.00	27.70	0.00	0.00	0.00	27.70
1968	0.00	2.61	6.47	34.30	0.00	0.00	0.00	43.38
1969	0.00	25.86	0.00	22.70	0.00	0.00	0.00	48.56
1970	2.42	26.20	5.88	0.00	0.00	0.00	0.00	34.50
1971	19.05	10.43	0.00	0.00	0.00	12.82	0.00	42.30
1972	20.99	6.48	0.00	0.00	0.00	12.52	0.00	40.00
1973	9.66	1.92	0.00	9.63	0.00	7.24	0.00	28.44
1974	8.13	0.00	0.00	12.54	0.00	6.96	0.00	27.62
1975	0.00	0.00	0.00	12.26	8.23	10.36	0.00	30.85
1976	0.00	2.78	0.00	13.63	9.44	12.68	0.00	38.52
1977	1.52	4.62	3.26	15.90	7.56	20.80	13.65	67.31
1978	8.54	5.73	8.42	14.59	13.41	9.12	8.14	67.94
1979	10.85	7.32	11.82	15.81	12.24	7.18	1.74	66.93
1980	9.15	7.48	7.50	10.52	14.47	6.63	3.38	59.13
1981	8.72	7.01	8.64	14.28	13.32	5.74	2.84	60.55
1982	8.92	6.85	9.05	14.23	5.71	8.86	0.00	53.62
1983	9.11	6.83	8.83	14.84	12.97	9.05	0.00	61.61
1984	9.88	7.31	8.81	14.50	13.52	8.95	0.00	62.96
1985	9.06	6.45	9.29	14.52	11.58	5.60	0.00	56.50
1986	8.24	6.83	9.12	14.35	12.08	4.18	0.00	54.80
1987	9.55	6.88	8.67	14.66	13.69	4.53	0.00	57.97
1988	9.43	6.81	8.57	14.83	11.82	6.54	0.00	58.00
1989	9.18	6.86	9.18	13.57	10.29	5.97	0.00	55.05
1990	8.94	6.97	9.32	15.29	12.87	6.37	0.00	59.76
1991	8.81	6.35	8.95	0.00	2.23	7.97	0.60	34.91
1992	9.32	6.87	8.88	0.00	0.00	0.00	0.00	25.08
1993	9.31	5.94	6.58	1.48	15.41	8.02	0.00	46.73
1994	0.00	3.86	0.00	1.64	16.29	7.18	0.00	28.96
1995	1.44	4.27	0.00	4.67	12.56	7.54	0.00	30.47
1996	2.35	4.91	0.00	10.21	16.91	4.50	0.00	38.89
1997	0.90	5.00	0.00	14.33	10.59	0.00	0.00	30.81
1998	1.43	5.14	0.00	19.83	17.07	0.00	0.00	43.47
1999	2.74	5.12	5.68	14.58	17.09	4.50	0.00	49.71
2000	0.00	5.21	5.81	16.93	17.31	0.00	0.00	45.26
2001	0.44	5.43	5.77	16.55	16.37	0.00	0.00	44.55
2002	0.00	4.77	7.62	16.23	16.71	0.00	0.00	45.32
2003	1.52	5.48	0.00	15.84	17.17	0.00	0.00	40.01
2004	3.27	6.91	9.01	14.70	7.57	0.00	0.00	41.45
2005	2.91	6.62	8.83	13.72	2.61	0.00	0.00	34.69
2006	8.81	7.60	7.48	14.27	12.78	0.00	0.00	50.94
2007	8.68	6.80	8.75	10.61	8.65	0.00	0.00	43.50
2008	8.80	7.59	7.46	14.50	13.60	0.00	0.00	51.94
2009		5.22	8.66	12.67	6.51	0.00	0.00	33.06
2010	2.53	3.32	9.07	20.43	0.00	0.00	0.00	35.36

Table 2. River-based quotas (tonnes) for Cambridge Bay Arctic Char commercial fisheries during 1960-2010.

Year	Lauchlan	Halovik	Paliryuak	Ekalluk	Jayco	Ellice	Perry	Sum
1960								
1961								
1962				18.16				18.16
1963				18.16				18.16
1964				18.16				18.16
1965				18.16				18.16
1966				18.16				18.16
1967								
1968								
1969								
1970								
1971						22.70		22.70
1972	18.16	9.10				11.35		38.61
1973	18.16	9.10		18.16		11.35		56.77
1974	11.35			11.35		11.35		34.05
1975				11.35	6.80	11.35		29.50
1976		9.10		11.35	6.80	13.60		40.85
1977	6.80	4.50	4.50	11.35	6.80	13.60	11.35	58.90
1978	6.80	4.50	6.80	11.35	11.35	13.60	11.35	65.75
1979	9.10	6.80	9.10	14.50	13.60	9.10	11.35	73.55
1980	9.10	6.80	9.10	14.50	13.60	9.10	11.35	73.55
1981	9.10	6.80	9.10	14.50	13.60	9.10	6.80	69.00
1982	9.10	6.80	9.10	14.50	13.60	9.10	6.80	69.00
1983	9.10	6.80	9.10	14.50	13.60	9.10	6.80	69.00
1984	9.10	6.80	9.10	14.50	13.60	9.10	6.80	69.00
1985	9.10	6.80	9.10	14.50	13.60	4.50	4.50	62.10
1986	9.10	6.80	9.10	14.50	13.60	4.50	4.50	62.10
1987	9.10	6.80	9.10	14.50	13.60	4.50	4.50	62.10
1988	9.10	6.80	9.10	14.50	13.60	6.00	4.50	63.60
1989	9.10	6.80	9.10	14.50	13.60	6.00	4.50	63.60
1990	9.10	6.80	9.10	14.50	13.60	6.00	4.50	63.60
1991	9.10	6.80	9.10	1.50	15.60	8.00	6.50	56.60
1992	9.10	6.80	9.10	7.50	15.60	8.00	6.50	62.60
1993	9.10	6.80	9.10	7.50	15.60	8.00	6.50	62.60
1994	9.10	5.00	0.00	20.00	17.00	8.00	6.50	65.60
1995	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
1996	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
1997	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
1998	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
1999	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
2000	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
2001	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
2002	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
2003	2.40	5.00	0.00	20.00	17.00	8.00	6.50	58.90
2004	9.10	6.80	9.10	14.50	13.60	8.00	6.50	67.60
2005	2.40	5.00	9.10	20.00	17.00	8.00	6.50	68.00
2006	2.40	5.00	9.10	20.00	17.00	8.00	6.50	68.00
2007	2.40	5.00	9.10	20.00	17.00	8.00	6.50	68.00
2008	2.40	5.00	9.10	20.00	17.00	8.00	6.50	68.00
2009	2.40	5.00	9.10	20.00	17.00	8.00	6.50	68.00
2010	2.40	5.00	9.10	20.00	17.00	8.00	6.50	68.00

Table 3. Harvest statistics for subsistence use of Arctic Char by the Aboriginal residents of Cambridge Bay, Nunavut. Data is from a Nunavut wildlife harvest study conducted during 1996-2001 (Priest and Usher 2004), showing the numbers of char caught and hunters for the fish over month and year.

Year	Number	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Total
1996	Arctic Char	205	2,601	1,155	25	43	64	313					38	4,444
1997	Arctic Char	194	668	328	110	35		22					80	1,437
1998	Arctic Char	813	1,084	1,416	1,235	26	168				1		2	4,745
1999	Arctic Char	977	4,087	3,063	965	129	21							9,242
2000	Arctic Char	915	2,956	5,309	2,009	522	11	129				54	530	12,435
	Mean	621	2,279	2,254	869	151	66	155			1	54	163	6,461
1996	Hunter	6	14	9	1	2	1	1					3	23
1997	Hunter	12	14	11	5	1		1					5	33
1998	Hunter	27	14	14	14	3	4				1		2	40
1999	Hunter	17	26	36	10	5	1							50
2000	Hunter	22	29	37	20	10	1	2				2	8	55
	Mean	17	19	21	10	4	2	1			1	2	5	40

Table 4. CPUE (tonnes/set) of Arctic Char from DFO-designed experimental gillnet and weir sampling programs in Cambridge Bay, Nunavut, during 1972-2006. Mean CPUE values are expressed as arithmetic (Arithmean) and geometric (Geomean) averages. AugGM and SepGM were CPUEs standardized by the months of August and September, respectively.

Year	Month	Location	Gear	Gear type	Arithmean	Geomean	AugGM	SepGM
1972	8	Ekalluk	gillnet	1	0.3889	0.3889	0.3889	0.5366
1978	8	Ekalluk	gillnet	1	0.0978	0.0550	0.0550	0.0759
1980	8	Paliryuak	gillnet	1	0.0839	0.0818	0.0818	0.1128
1991	8	Ekalluk	gillnet	1	0.2225	0.2124	0.2124	0.2931
1992	8	Ekalluk	gillnet	1	0.1239	0.1111	0.1111	0.1533
2006	8	Halovik	gillnet	1	0.1221	0.0954	0.0954	0.1316
1975	8	Jayco	weir	2	0.0123	0.0064	0.0064	0.0088
1979	8	Ekalluk	weir	2	0.1632	0.1250	0.1250	0.1724
1980	8	Jayco	weir	2	0.2226	0.1659	0.1659	0.2289
1981	8	Jayco	weir	2	0.1496	0.1324	0.1324	0.1826
1981	8	Halovik	weir	2	0.3574	0.2970	0.2970	0.4098
1983	8	Lauchlan	weir	2	0.1088	0.0341	0.0341	0.0470
1978	9	Ekalluk	gillnet	1	0.2640	0.2474	0.1793	0.2474
1980	9	Paliryuak	gillnet	1	0.0298	0.0257	0.0186	0.0257
1988	9	Ekalluk	gillnet	1	0.1902	0.1415	0.1026	0.1415
2005	9	Jayco	gillnet	1	0.1493	0.1493	0.1082	0.1493
1975	9	Jayco	weir	2	0.1213	0.0739	0.0536	0.0739
1979	9	Ekalluk	weir	2	0.3105	0.2002	0.1451	0.2002
1980	9	Jayco	weir	2	0.2019	0.1951	0.1414	0.1951
1981	9	Halovik	weir	2	0.1791	0.1461	0.1059	0.1461
1981	9	Jayco	weir	2	0.3867	0.3762	0.2727	0.3762
1983	9	Lauchlan	weir	2	0.4187	0.4053	0.2937	0.4053

Table 5. ANOVA results for log-transformed CPUEs of Arctic Char by month (July vs September) and gear type (gillnet vs weir), sampled in Cambridge Bay during 1972-2006.

Source	Partial SS	*df*	MS	*F*	Prob>*F*
Model	8.31	4	2.08	2.17	0.11
Month	5.65	1	2.83	2.96	0.08
Gear type	0.01	1	0.01	0.02	0.90
Month X gear type	1.72	1	1.72	1.80	0.20
Residual	17.21	18	0.96		
Total	25.52	22	1.16		

Table 6. Pair-wise correlation between log-transformed CPUE and the North Atlantic oscillation (NAO) index. Parameters r and p are Pearson correlation coefficients and critical values. Bold numbers indicate significant correlation coefficients at the critical level α=0.05. The red-colored numbers were selected for the subsequent analysis.

Month	Parameter	Lag (in years)										
		0	1	2	3	4	5	6	7	8	9	10
Jan	*r*	0.0753	-0.4733	-0.1131	-0.0018	-0.0678	**0.6069***	-0.0914	0.2615	0.2199	0.3805	0.0308
	p	0.8258	0.1414	0.7406	0.9959	0.8430	**0.0477**	0.7893	0.4374	0.5160	0.2483	0.9285
Feb	*r*	0.2249	0.1578	0.0080	-0.2917	-0.5632	-0.2706	0.2008	**0.6604***	-0.0506	0.3451	0.3437
	p	0.5062	0.6431	0.9813	0.3842	0.0712	0.4209	0.5537	**0.0270**	0.8826	0.2986	0.3007
Mar	*r*	0.1679	0.3706	-0.0819	-0.2462	0.1260	**0.7551***	0.1843	-0.1225	-0.4448	-0.1421	0.1707
	p	0.6217	0.2618	0.8107	0.4656	0.7120	**0.0072**	0.5875	0.7197	0.1705	0.6768	0.6157
Apr	*r*	0.0578	0.2375	-0.1023	-0.0801	0.0461	0.1451	-0.5819	**0.6766***	-0.4040	0.3316	-0.1949
	p	0.8660	0.4820	0.7647	0.8149	0.8929	0.6704	0.0604	**0.0222**	0.2179	0.3191	0.5659
May	*r*	0.1126	-0.1639	0.1556	-0.2308	-0.4109	-0.0010	-0.5375	0.5774	0.2305	0.0199	0.2106
	p	0.7417	0.6301	0.6477	0.4947	0.2093	0.9977	0.0882	0.0629	0.4952	0.9537	0.5343
Jun	*r*	0.2456	-0.1620	0.0539	0.0359	0.1771	0.0752	-0.3931	-0.1513	-0.1178	-0.0929	-0.2255
	p	0.4666	0.6342	0.8748	0.9165	0.6024	0.8261	0.2317	0.6570	0.7301	0.7858	0.5050
Jul	*r*	-0.4350	0.3747	-0.0606	-0.2855	0.0463	-0.2702	0.2326	0.1144	0.4354	-0.1305	-0.1493
	p	0.1812	0.2561	0.8594	0.3948	0.8924	0.4217	0.4912	0.7378	0.1808	0.7021	0.6613
Aug	*r*	0.4913	-0.0849	0.1922	-0.3616	-0.5406	0.1950	0.5046	0.4990	-0.2327	0.3170	-0.0497
	p	0.1249	0.8040	0.5713	0.2746	0.0860	0.5655	0.1135	0.1182	0.4911	0.3422	0.8847
Sept	*r*	-0.4116	0.0936	0.1147	-0.0665	0.1288	-0.1304	-0.2916	0.4175	-0.0442	0.3526	-0.1409
	p	0.2085	0.7844	0.7371	0.8459	0.7059	0.7023	0.3842	0.2014	0.8974	0.2876	0.6794
Oct	*r*	0.2584	-0.2232	1.1374	-0.2267	0.1123	0.5917	-0.3009	0.5979	-0.2152	0.3709	-0.1653
	p	0.4429	0.5094	0.6871	0.5027	0.7424	0.0552	0.3686	0.0520	0.5250	0.2615	0.6271
Nov	*r*	-0.1721	0.3174	0.1452	0.0847	0.3912	0.4032	0.1903	0.3612	-0.5764	0.2779	0.1422
	p	0.6128	0.3415	0.6701	0.8044	0.2342	0.2188	0.5751	0.2750	0.0634	0.4081	0.6765
Dec	*r*	-0.0902	-0.1505	-0.1600	-0.1499	-0.0290	0.1456	0.0110	0.2587	0.1327	0.1136	-0.2118
	p	0.7921	0.6588	0.6385	0.6600	0.9325	0.6693	0.9743	0.4424	0.6972	0.7395	0.5319

Table 7. Pair-wise correlation between log-transformed CPUE and the Arctic oscillation index (AOI). Parameters r and p are Pearson correlation coefficients and critical values. Bold numbers indicate significant correlation coefficients at the critical level α=0.05. The red-colored numbers were selected for the subsequent analysis.

Month	Parameter	Lag (in years)										
		0	1	2	3	4	5	6	7	8	9	10
Jan	*r*	-0.1934	-0.2802	-0.1887	-0.0986	-0.4777	0.5111	0.1399	0.2033	0.3979	0.3670	0.3608
	p	0.5689	0.4040	0.5785	0.7731	0.1373	0.1081	0.6816	0.5488	0.2256	0.2669	0.2757
Feb	*r*	-0.4368	0.2171	-0.0027	-0.2696	-0.2893	0.0386	0.3630	0.5509	-0.3134	0.1598	0.1764
	p	0.1792	0.5214	0.9938	0.4227	0.3882	0.9102	0.2726	0.0791	0.3480	0.6387	0.6039
Mar	*r*	-0.2873	0.4028	-0.2744	-0.2037	-0.0630	**0.7858***	0.4371	-0.5347	-0.3147	0.0633	0.0913
	p	0.3917	0.2194	0.4142	0.5481	0.8540	**0.0041**	0.1788	0.0902	0.3457	0.8534	0.7894
Apr	*r*	-0.2047	0.1946	0.2072	-0.5808	0.2817	-0.3417	0.1807	-0.0243	**-0.7333***	**0.6907***	-0.2572
	p	0.5459	0.5664	0.5410	0.0610	0.4013	0.3033	0.5948	0.9434	**0.0102**	**0.0186**	0.4452
May	*r*	0.1569	0.1807	0.1044	-0.4910	-0.3276	-0.2335	0.0359	0.2140	-0.2660	-0.4175	0.2094
	p	0.6451	0.5949	0.7600	0.1252	0.3254	0.4895	0.9166	0.5275	0.4291	0.2014	0.5366
Jun	*r*	0.0095	0.0284	-0.1135	0.4395	0.2007	-0.0100	-0.0781	-0.3347	-0.1053	-0.1589	-0.1367
	p	0.9779	0.9340	0.7396	0.1762	0.5539	0.9766	0.8195	0.3144	0.7579	0.6408	0.6886
Jul	*r*	-0.0983	**-0.7164***	0.2045	-0.0675	0.1729	-0.2923	-0.2799	0.4432	0.0304	0.1060	0.1311
	p	0.7737	**0.0131**	0.5464	0.8437	0.6113	0.3831	0.4045	0.1722	0.9294	0.7564	0.7009
Aug	*r*	0.1716	0.0833	-0.1819	0.0808	**-0.7163***	0.0179	0.1885	0.4871	0.3912	0.1467	0.2206
	p	0.6139	0.8075	0.5924	0.8133	**0.0132**	0.9583	0.5789	0.1287	0.2342	0.6670	0.5145
Sept	*r*	**-0.6153***	0.2028	-0.1801	0.3827	0.0917	-0.1755	0.3623	0.0992	0.3968	-0.2378	0.2219
	p	**0.0439**	0.5498	0.5961	0.2454	0.7886	0.6058	0.2735	0.7716	0.2269	0.4814	0.5119
Oct	*r*	0.0275	0.4697	-0.3034	-0.0991	-0.3620	0.0474	0.0842	0.0181	-0.1948	0.1689	-0.0746
	p	0.9361	0.1450	0.3645	0.7719	0.2739	0.8900	0.8055	0.9579	0.5659	0.6195	0.8274
Nov	*r*	-0.1717	0.1397	-0.0871	0.1281	0.1230	0.1068	0.0435	0.4300	0.0927	0.0761	0.2383
	p	0.6138	0.6821	0.7989	0.7074	0.7186	0.7545	0.8990	0.1869	0.7864	0.8241	0.4805
Dec	*r*	-0.3590	0.0778	-0.1306	-0.2648	-0.0057	-0.1606	0.4432	0.1447	0.1109	0.4447	-0.1074
	p	0.2783	0.8202	0.7019	0.4314	0.9868	0.6370	0.1722	0.6712	0.7454	0.1705	0.7532

Table 8. Pair-wise correlation between log-transformed CPUE and northern hemisphere sea surface temperatures (NHSST). Parameters r and p are Pearson correlation coefficients and critical values. None of the correlation coefficients were significant at the critical level α=0.05.

Month	Parameter	Lag (in years)										
		0	1	2	3	4	5	6	7	8	9	10
Jan	*r*	0.2889	0.2317	-0.3706	0.3409	-0.1181	-0.3720	-0.5277	-0.1644	0.0162	-0.4442	0.3234
	p	0.3889	0.4931	0.2618	0.3050	0.7295	0.2600	0.0953	0.6290	0.9623	0.1711	0.3319
Feb	*r*	0.1400	0.2029	-0.3813	0.1849	0.0007	-0.4089	-0.4805	-0.1327	-0.0429	-0.4217	0.2237
	p	0.6813	0.5497	0.2473	0.5862	0.9984	0.2118	0.1346	0.6973	0.9003	0.1964	0.5085
Mar	*r*	0.3768	0.3225	-0.2697	0.1818	0.1029	-0.3756	-0.4738	-0.0369	-0.0889	-0.4348	0.2472
	p	0.2533	0.3334	0.4226	0.5927	0.7635	0.2550	0.1410	0.9141	0.7948	0.1814	0.4637
Apr	*r*	0.3158	0.1902	-0.2374	-0.0174	-0.0240	-0.4608	-0.5433	-0.1712	-0.2547	-0.3269	0.3037
	p	0.3441	0.5754	0.4822	0.9595	0.9441	0.1537	0.0841	0.6148	0.4498	0.3264	0.3638
May	*r*	0.2525	0.2590	-0.1950	-0.1269	0.0537	-0.3258	-0.5492	-0.3318	-0.2529	-0.1345	0.2140
	p	0.4538	0.4418	0.5656	0.7100	0.8754	0.3283	0.0802	0.3189	0.4532	0.6934	0.5275
Jun	*r*	0.3488	0.1237	-0.0224	-0.1451	0.1571	-0.2836	-0.3805	-0.4039	-0.2520	-0.2038	0.1790
	p	0.2931	0.7170	0.9480	0.6703	0.6447	0.3980	0.2483	0.2179	0.4547	0.5478	0.5985
Jul	*r*	0.2625	0.1098	-0.0526	-0.1515	0.0892	-0.1488	-0.3337	-0.2863	-0.2782	-0.3253	0.3168
	p	0.4355	0.7479	0.8779	0.6565	0.7943	0.6623	0.3160	0.3934	0.4074	0.3290	0.3425
Aug	*r*	0.1473	0.0050	-0.0480	-0.1149	0.2367	-0.2520	-0.3606	-0.2175	-0.3527	-0.3148	0.0045
	p	0.6656	0.9883	0.8887	0.7365	0.4834	0.4546	0.2759	0.5205	0.2875	0.3458	0.9894
Sep	*r*	0.2535	0.0948	0.0221	-0.1388	0.3069	-0.2163	-0.3654	-0.4012	-0.2719	-0.2889	-0.0279
	p	0.4519	0.7815	0.9485	0.6840	0.3587	0.5230	0.2694	0.2214	0.4185	0.3880	0.9350
Oct	*r*	0.2585	0.1574	0.0462	-0.1699	0.1811	-0.2385	-0.3850	-0.4208	-0.3306	-0.3579	-0.2699
	p	0.4428	0.6438	0.8927	0.6174	0.5940	0.4800	0.2423	0.1975	0.3208	0.2798	0.4222
Nov	*r*	0.2665	0.2330	0.0437	-0.2882	0.2664	-0.1943	-0.3939	-0.4418	-0.1343	-0.2811	-0.4119
	p	0.4283	0.4905	0.8984	0.3901	0.4284	0.5670	0.2307	0.1737	0.3465	0.4024	0.2082
Dec	*r*	0.3676	0.2089	0.2011	-0.3308	0.1897	-0.1908	-0.4550	-0.4056	-0.2540	-0.1964	-0.3828
	p	0.2661	0.5376	0.5533	0.3203	0.5763	0.5741	0.1597	0.2158	0.4510	0.5626	0.2453

Table 9. Summary of the deviance information criterion (DIC) for model selection for normal regression models with respect to sixteen parameter combinations used to account for the impacts of a constant, year, AOI, NAO, and NHSST on log-transformed Arctic Char CPUE sampled in summer. The analysis also considered five-year lag effects in terms of pair-wise correlation analyses. R^2_B and SD were posterior precisions for the mean and expected standard deviation, respectively. $\overline{D}$ and D were the posterior mean deviance and the deviance at the posterior mean, respectively. D is a measure of model complexity, roughly speaking the number of parameters in the model. The best model was selected based on the smallest DIC and is represented by bold values.

Model	R^2_B	SD	$\overline{D}$	D	pD	DIC
AOI	**0.5318**	**0.3403**	**7.74**	**4.48**	**3.26**	**11.00**
Year, AOI	0.5419	0.3366	7.54	3.68	3.86	11.40
AOI, NAO	0.5613	0.3294	7.09	2.66	4.43	11.52
Year, AOI, NHSST	0.5702	0.3260	7.11	2.14	4.97	12.08
NAO	0.4736	0.3608	9.02	5.75	3.26	12.28
Year, AO, NAO	0.5534	0.3323	7.39	2.24	5.15	12.54
AOI, NHSST	0.4706	0.3618	9.20	4.77	4.42	13.62
Year, NAO	0.4349	0.3738	9.85	6.01	3.84	13.69
Year, NAO, NHSST	0.4771	0.3596	9.22	4.32	4.91	14.13
Year, AOI, NAO, NHSST	0.5232	0.3434	8.04	1.87	6.17	14.21
NAO, NHSST	0.4389	0.3725	9.84	5.42	4.42	14.26
AOI, NAO, NHSST	0.4919	0.3545	8.73	3.10	5.63	14.37
Year, NHSST	0.0731	0.4788	15.23	11.70	3.53	18.76
Constant	-0.0771	0.5161	16.99	14.85	2.13	19.12
NHSST	-0.0434	0.5080	16.61	13.35	3.26	19.87
Year	-0.1351	0.5298	17.57	14.89	2.68	20.25

Table 10. Summaries of OpenBUGS posteriors for a normal regression model of log-transformed Arctic Char CPUE in Cambridge Bay, Nunavut, and monthly AOI anomalies with a five-year lag, after 3,000,000 iterations and an additional discard of 50,000 burn-in iterations. CPUE data were modeled from (a) the best model with the smallest DIC, or (b) the model with the highest R^2_B. R^2_B, SD and MC error were posterior values of mean precision, standard deviation and Monte Carlo error, respectively. Parameters β and μ are regression coefficients.

(a)

Node	Mean	SD	MC error	2.5%	Median	97.5%	Start	Sample
R^2_B	0.5491	0.2492	2.67E-03	-0.1104	0.6105	0.8253	500,000	20,000
β_1	-1.7000	0.1192	1.30E-03	-1.9340	-1.7010	-1.4620	500,000	20,000
β_2	0.3768	0.0932	8.98E-04	0.1894	0.3771	0.5634	500,000	20,000
1972	-0.9589	0.2297	2.33E-03	-1.4150	-0.9574	-0.5042	500,000	20,000
1975	-2.4850	0.2158	2.13E-03	-2.9100	-2.4890	-2.0490	500,000	20,000
1978	-1.4980	0.1344	1.45E-03	-1.7600	-1.4980	-1.2250	500,000	20,000
1979	-1.9810	0.1309	1.38E-03	-2.2420	-1.9820	-1.7180	500,000	20,000
1980	-1.6430	0.1216	1.33E-03	-1.8800	-1.6450	-1.3990	500,000	20,000
1981	-1.4790	0.1367	1.47E-03	-1.7460	-1.4790	-1.2020	500,000	20,000
1983	-1.5110	0.1329	1.43E-03	-1.7700	-1.5110	-1.2410	500,000	20,000
1988	-1.9140	0.1247	1.33E-03	-2.1610	-1.9160	-1.6600	500,000	20,000
1991	-0.9724	0.2269	2.30E-03	-1.4210	-0.9716	-0.5220	500,000	20,000
1992	-2.3580	0.1903	1.90E-03	-2.7350	-2.3610	-1.9720	500,000	20,000
2005	-1.8700	0.1217	1.31E-03	-2.1120	-1.8720	-1.6210	500,000	20,000
2006	-2.3360	0.1860	1.86E-03	-2.7030	-2.3380	-1.9570	500,000	20,000
SD	0.3983	0.0995	1.05E-03	0.2556	0.3816	0.6448	500,000	20,000

(b)

Node	Mean	SD	MC error	2.5%	Median	97.5%	Start	Sample
R^2_B	0.4656	0.3911	7.30E-03	-0.5215	0.5702	0.8243	500,000	20,000
β_1	-29.9000	20.8700	1.32E+00	-65.7900	-31.5400	13.8000	500,000	20,000
β_2	0.0141	0.0105	6.64E-04	-0.0079	0.0149	0.0322	500,000	20,000
β_3	0.2927	0.1067	1.30E-03	0.0800	0.2923	0.5098	500,000	20,000
β_4	-0.1145	31.6400	2.24E-01	-62.1300	-0.2284	62.4400	500,000	20,000
β_5	-0.8126	0.9625	3.47E-02	-2.6260	-0.8489	1.2030	500,000	20,000
μ_1	-2.7080	0.2390	7.49E-03	-3.1630	-2.7170	-2.2100	500,000	20,000
μ_2	-1.9250	0.2172	9.17E-03	-2.3300	-1.9350	-1.4600	500,000	20,000
μ_3	-2.0790	0.2118	2.19E-03	-2.5070	-2.0780	-1.6650	500,000	20,000
μ_4	-1.8480	0.1472	1.14E-03	-2.1410	-1.8490	-1.5540	500,000	20,000
μ_5	-1.6470	0.1894	2.49E-03	-2.0340	-1.6440	-1.2760	500,000	20,000
μ_6	-1.7990	0.1439	3.11E-03	-2.0800	-1.8020	-1.5040	500,000	20,000
μ_7	-2.1020	0.1184	1.36E-03	-2.3340	-2.1020	-1.8620	500,000	20,000
μ_8	-1.1870	0.2475	4.63E-03	-1.7010	-1.1830	-0.7071	500,000	20,000
μ_9	-2.3390	0.2058	5.19E-03	-2.7660	-2.3320	-1.9390	500,000	20,000
μ_{10}	-1.9710	0.2192	4.29E-03	-2.4150	-1.9680	-1.5380	500,000	20,000
μ_{11}	-2.3680	0.2467	4.28E-03	-2.8690	-2.3640	-1.8730	500,000	20,000
SD	0.3477	0.1063	2.05E-03	0.2085	0.3260	0.6135	500,000	20,000

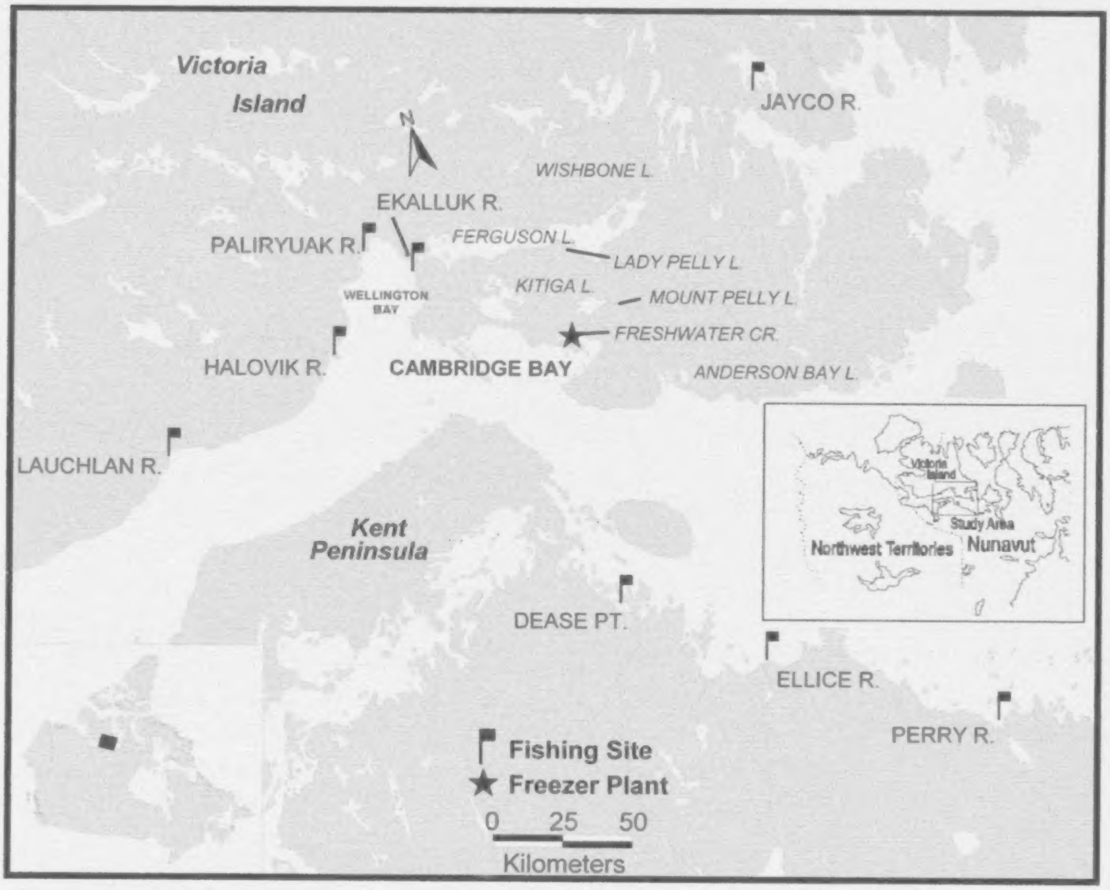

Figure 1. Map of Cambridge Bay, Nunavut, Canada, showing fishing locations for commercial and subsistence uses of Arctic Char (after Kristofferson and Berks 2005).

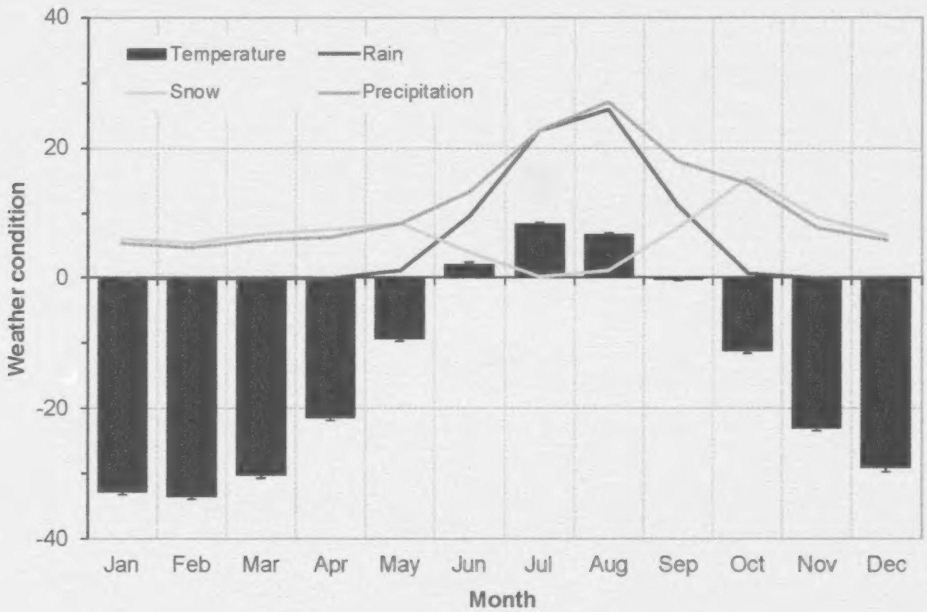

Figure 2. Monthly averages of air temperature (°C), rain (mm), snowfall (cm) and total precipitation (mm) in Cambridge Bay, Nunavut, during the period 1950-2010. Data source: Climate ID: 2400600, WMO ID: 71925, TC ID: YCB.

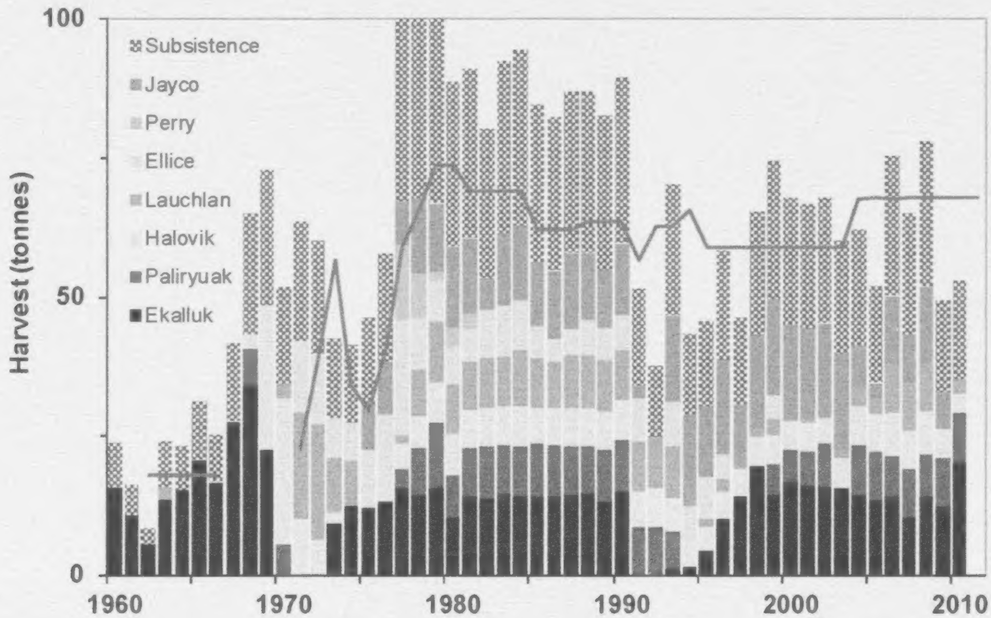

Figure 3. Changes in harvest of Arctic Char from the Cambridge Bay fisheries during 1960-2010. Coloured bars indicate commercial fisheries in individual rivers and hatched bars show estimated subsistence fisheries. The brown line indicates the allowable quota.

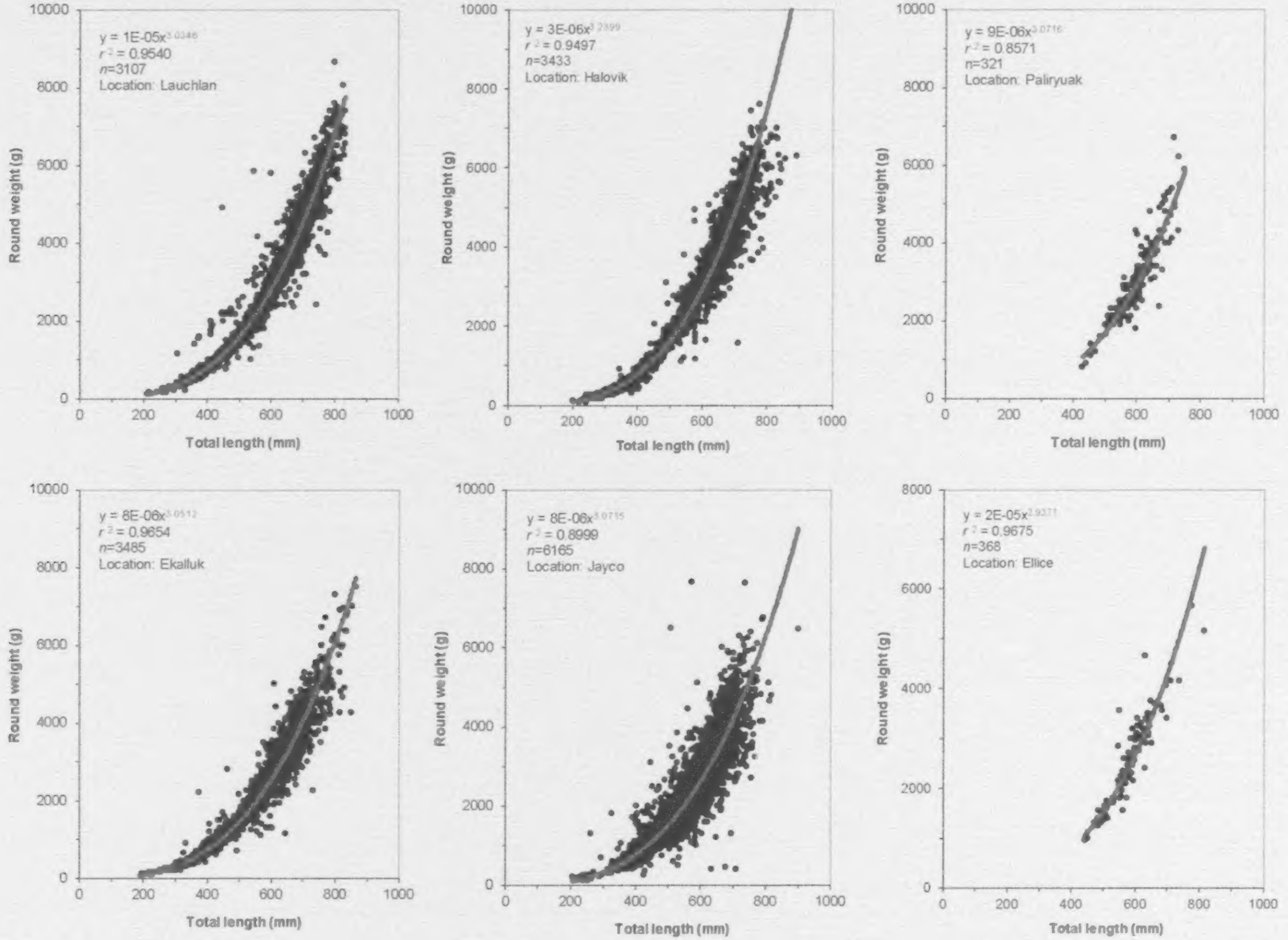

Figure 4. Relationship between total length (mm) and round weight (g) for Cambridge Bay Arctic Char sampled from six fishing locations during 1972-2006.

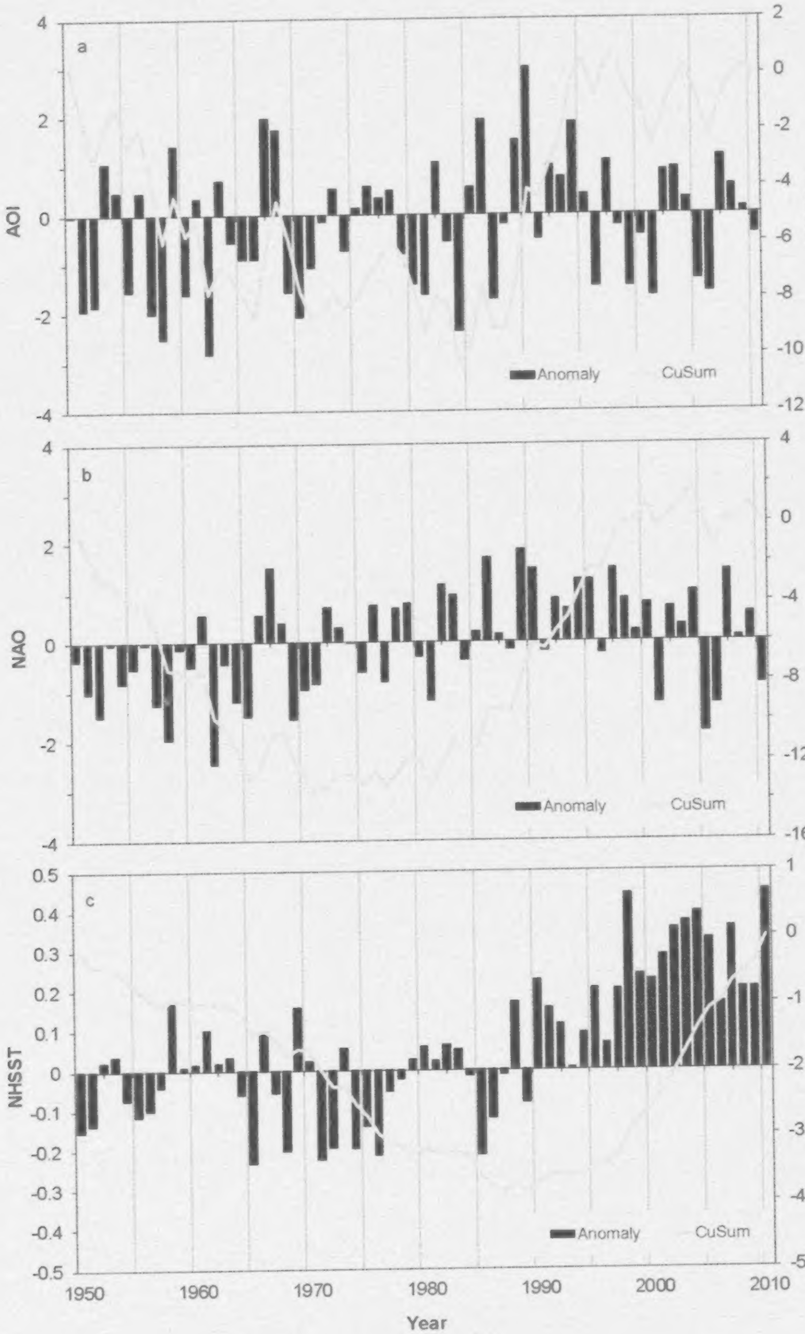

Figure 5. Anomalies in wintertime (represented by March) (a) North Atlantic oscillation index (NAO), (b) Arctic oscillation index (AOI), and (c) northern hemisphere sea surface temperature (NHSST) during 1950-2010. The cumulative sum of the control charts (CuSum) is represented by a line of circles. The trend of distinctly higher air pressure and lower temperature until mid-1970, followed by a period of lower air pressure and higher temperature, was termed a regime shift (Beamish et al. 1999).

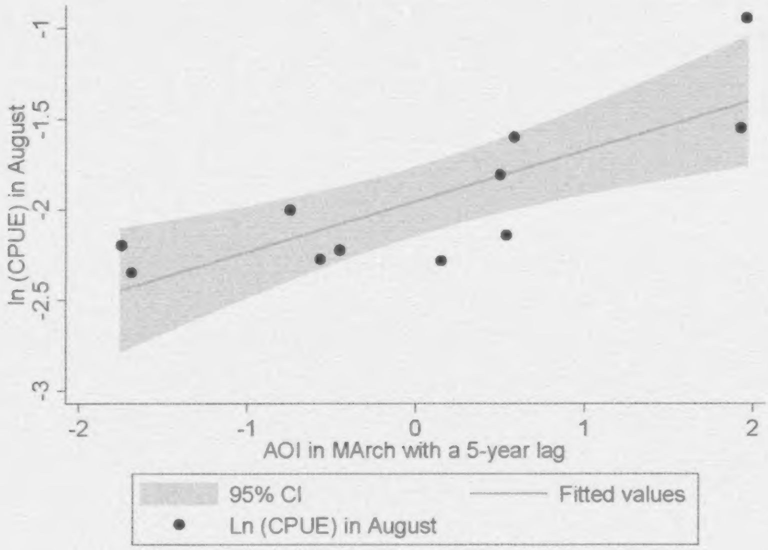

Figure 6. Regression between log-transformed CPUE and wintertime AOI. CPUE was standardized using gillnet data collected in August. Wintertime AOI refers to monthly anomalies in March with a five-year lag. The shaded area indicates the 95% confident intervals.

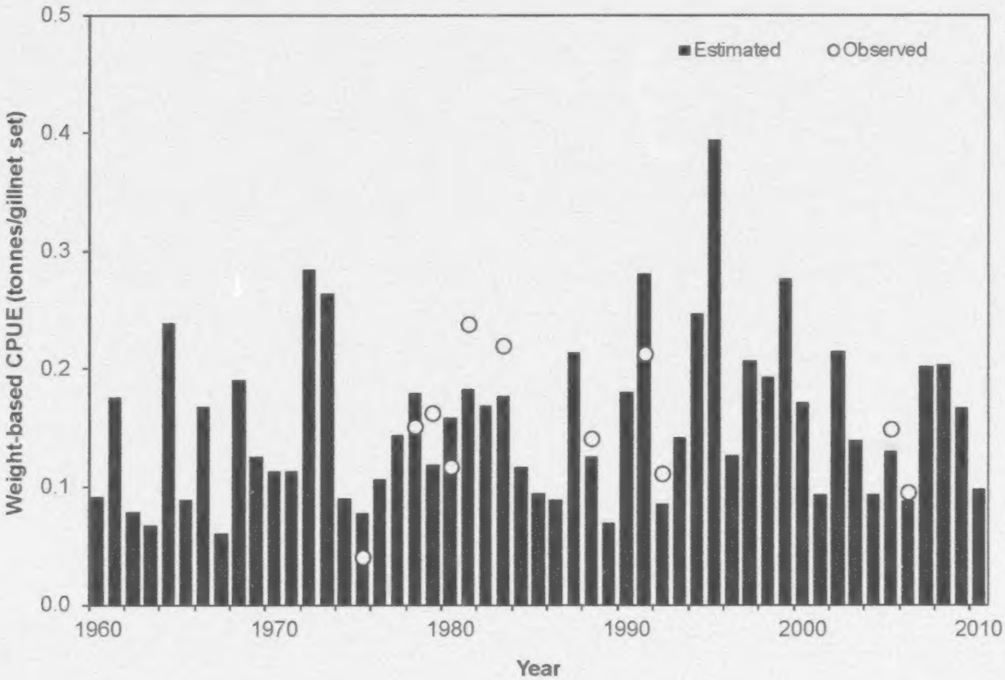

Figure 7. Comparison between observed (open dots) and predicted (black bars) CPUE for Arctic Char. The first observed data (1975) seemed strongly biased and was removed because of evident observation errors.

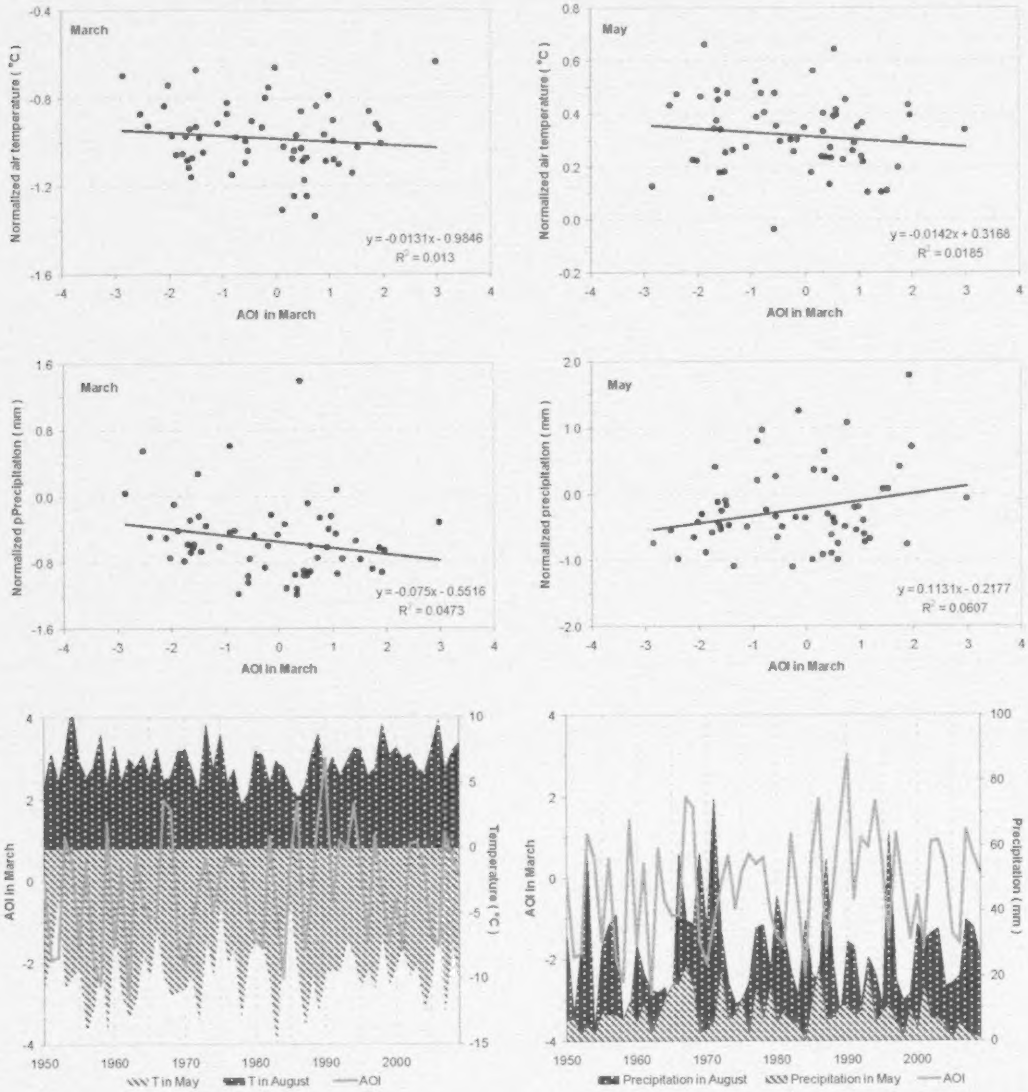

Figure 8. Correlation between wintertime AOI anomalies and normalized air temperature (upper) and precipitation (middle) in winter (March) and spring (May) in Cambridge Bay, Nunavut, during 1950-2009. The regression coefficients were not significant at the critical level α=0.05. The lower panels show local air temperature (left) and precipitation (right) in May and August (area), with AOI in March (line).